Bespoke Reinforcement for Optimised Concrete Structures

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Abstract

Flexible formwork for concrete structures has been shown to be an appropriate method for the construction of optimised concrete structures (Veenendaal *et al.* [1], Orr *et al.* [2]). With the goal of achieving low carbon design, two major challenges exist: 1) to reinforce structures with complex geometries and 2) to provide durable and resilient infrastructures. Meeting both challenges would allow one to capitalise on the fluidity of concrete to meet long-term emissions reductions targets. This will require an entirely new approach to design and construction of concrete structures.

Research underway at the University of Bath is attempting to completely replace internal steel reinforcement with a knitted composite cage made from fibre reinforced polymer (FRP) reinforcement. By fabricating the cage in exactly the right geometry, it will be possible to provide the required strength exactly where it is needed.

This paper will outline ongoing work which aims demonstrate that CFRP can be woven into geometrically appropriate ‘cages’ for the reinforcement of concrete beams, including consideration of the manufacturing process, construction technique, and technical design requirements.

Keywords: FRP, reinforcement, optimization, carbon, fibres, fabric formwork.

1. Introduction

1.1 Aged concrete structures and infrastructures

Reinforced Concrete (RC) is the most common construction material in the world. Unfortunately, phenomena such as depassivation of steel and carbonation of concrete, in the presence of moisture, produce corrosion of the steel reinforcement (Ahmad [3]). These phenomenona can substantially compromise the integrity of RC structures that, in order to ensure public safety, have to be rehabilitated. Eventually, demolition and rebuilding of concrete structures as well as building new concrete structures create a considerable environmental impact, as the manufacture of cement accounts for at least 5% of global CO_2 emissions.

1.2 FRP reinforcement: How may it help?

Fibre-reinforced polymer (FRP) reinforcing bars have been considered as an alternative to steel bars since the late 1980s (Plecnik and Ahmad [4]). They consist of a fibrous reinforcing phase embedded into a polymer matrix. The fibres provide strength and stiffness to the composite and carry most of the applied load while the resin encapsulates them, thus transferring stresses and providing protection

(Kaw [5]). Over the past two decades, laboratory tests and field applications have demonstrated that FRP bars possess a series of characteristics (such as high specific tensile strength and stiffness as well as corrosion resistance) that make their use advisable and cost-effective in many civil engineering applications (Nanni [6]). To date, FRP reinforcing bars have gained acceptance, especially in North America, as internal reinforcement in concrete structures but their use is still very limited to specific applications, such as bridge decks, traffic barriers and marine infrastructure (ACI Committee 440 [7]).

1.3 Some issues related to the use of FRP reinforcement

Several global activities have taken place to implement FRP rebars into design codes and guidelines (JSCE [8], ACI 440 [9], AASHTO [10], CNR [11], fib [12], CSA S6-06 [13], CSA S806-12 [14]). However, in spite of the substantial work already done so far, many issues involved with the use of FRP rebars in new concrete structures still demand further investigation.

Unlike steel bars, which exhibit yielding and plastic flow, FRP bars are characterised by a stress–strain relationship that is linear-elastic up to failure. FRP bars have excellent mechanical properties in the direction of the fibres and due to the nature of the fibres and resin before best when loaded in axial tension. Consequently, the design criteria developed over the years for structures reinforced with steel bars cannot be directly applied to FRP RC structures.

Moreover, FRP reinforcement cannot be bent and shaped on site in order to obtain conventional reinforcement cages. Longitudinal bars (normally produced through a pultrusion process in lengths that are suitable for transportation) can be lapped and/or cut on site depending on needs. However, stirrups need to be factory produced in the exact shape required with no possibility of modifying them on site. Thus flexibility in the construction process is limited. In order to improve their effectiveness, stirrups are normally produced as closed shapes.

Although all these problems would suggest looking at FRP RC structures from a different point of view, the construction industry still tends to adopt the technical knowledge derived from steel reinforcement to FRP RC structures.

2.1 Low carbon design of concrete structures using FRP reinforcement

New frontiers of research in the field of construction are moving towards holistic design and management of sustainable and resilient infrastructure systems. Given this, the qualities of durability and high mechanical performance of FRP bars may help to solve the problem of corrosion of steel reinforcement.

Moreover, extensive applications of innovative materials require deep knowledge of their characteristics, structural behaviour and implication for reliable and sustainable long-term service (Nanni *et al.* [15]). This means not only good performance to resist degradation, but also the ability to limit the impact of the construction process on the natural environment. Recent research has made it possible to cast geometrically complex concrete structures, capitalizing on a key advantage of this fluid material (Veenendaal *et al.* [1], Orr *et al.* [2]). These developments allow new architectural expression, and the new geometries can help us save considerable amounts of material that may help the sustainability in the construction process (Figure 1). With this in mind, the optimal design of the geometry of FRP reinforced concrete structures through computation will help to achieve targets for the reduction of emissions by drastically limiting the use of raw materials.

In addition to shaping our structures geometrically, further savings in emissions can be achieved through the use of low-carbon cements, which further reduce the embodied energy of concrete (Heat *et al.* [16]). However, such cements cannot readily be used with steel reinforcement as they also reduce the alkalinity of the concrete mix. By contrast, a reduced alkalinity environment makes no difference to carbon fibre reinforcement, allowing the potential to achieve embodied energy savings through both geometry and material choices.

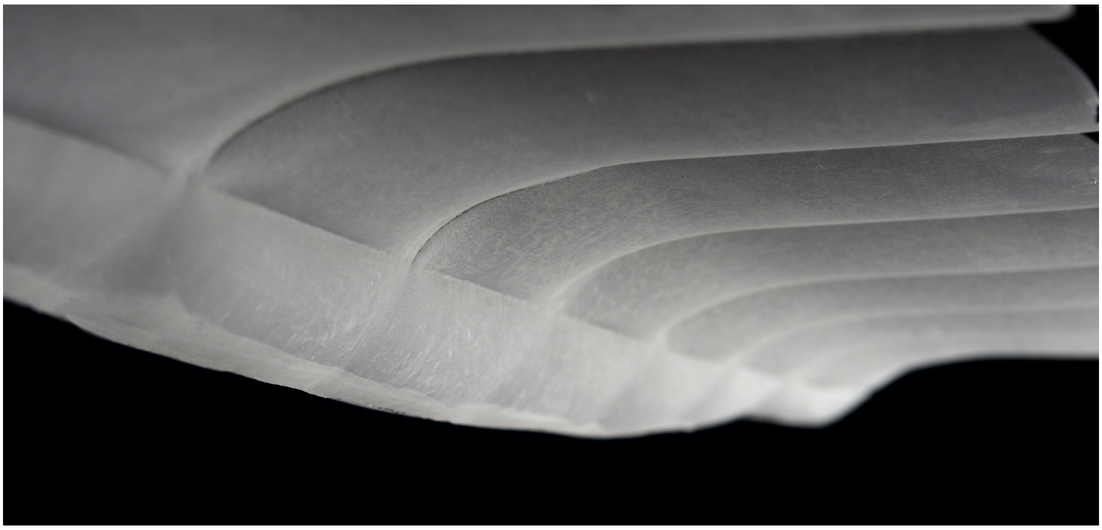

Figure 1: Image of an optimised, flexibly formed, concrete T-beam.

Research in progress at the University of Bath aims to explore the possibility of fabricating the FRP reinforcement cages in an optimized geometry, in order to provide the tensile strength given by reinforcing bars exactly where it is needed and consequently limit the volume of concrete used. This will be transformative for concrete construction, as it will greatly simplify the design of more efficient, thin walled and architecturally daring concrete structures.

An experimental program will be performed at the University of Bath in order to demonstrate the feasibility and effectiveness of the proposed construction method.

2. Materials and Methods

The main idea of this research is to produce continuous CFRP spirals that will provide the shear reinforcement in beams with a variable cross section, while commercially available CFRP bars will provide their flexural strength. The CFRP spirals will be manufactured by mean of an automated process and post-assembled with longitudinal reinforcing bars so as to obtain light and ready-to-use reinforcement cages. This sort of CFRP cage will be enough light to be easily transported on construction sites while the use of fabric to form and cast concrete members will allow the production of optimized shape of concrete members.

The idea of incorporating continuous FRP spirals as shear reinforcement and reinforcing longitudinal bars into fabric formed concrete derives from the flexibility that FRP reinforcement can guarantee during manufacturing process and the non-uniform shapes that can be produced by fabric formwork. This will permit the full exploitation of the potential of the FRP reinforcement and avoid the typical problems encountered in using them in a conventional manner (bars cannot be bent after the polymerization process has happened).

2.1 Reinforcing cages: manufacturing process and mechanical properties

The non-uniform spirals, which will be used as web reinforcement of the beams, will be manufactured at University of Bath using a modified filament winding fabrication technique. Filament winding consists of winding continuous filaments under tension over a mandrel in predetermined patterns. The mandrel rotates while a wind eye on a carriage moves horizontally, laying down fibres in the desired pattern. This method of manufacturing provides the greatest control over fibre placement and uniformity of structure. In the wet winding method, the fibre picks up resin either by passing through a resin bath or from a metered application system. In the dry winding method, the reinforcement is in the pre-impregnated form (pre-preg). After several layers are wound, the component is cured and removed from the mandrel.

This process is well suited to automation and is normally used to produce hollow shapes with constant cross section. In this case, a refined system of control will allow the production of CFRP cages in the form of rectangular spirals with variable cross section (Figure 2).

Figure 2: Examples of filament wound FRP shear reinforcement

It is proposed that standard modulus carbon fibres may be used for such reinforcement, rather than high modulus carbon fibres which are more frequently used in aerospace applications. The typical properties of standard modulus carbon fibres shown in Table 1 demonstrate that such fibres are appropriate for most structural engineering uses.

Table 1: Properties of typical standard-modulus carbon fibres

Tensile Strength	> 3500 MPa
Ultimate Strain	> 1.5 %
E-Modulus	> 240 GPa

However, the values of Young modulus of elasticity, E_f , and ultimate strength at failure, f_u , of an FRP material are always lower than those of the fibre itself, while the ultimate tensile strain is of the same order of magnitude for both materials. For this reason the mechanical properties of the FRP material composing the spirals, as obtained through the filament winding manufacturing process, will be carefully characterised in the laboratory in later work.

2.2 Fabric Formwork

Fabric formwork describes a method of construction for concrete elements in which rectangular sheets of fabric are used in lieu of steel or timber moulds. It allow complex shapes to be easily cast, thus facilitating the construction of optimised structures (Veenendaal *et al.* [1], Orr *et al.* [2]). As architects and the construction industry are attracted by the new possibilities of building unconventional concrete shapes, work is underway around the world to develop systems for the design of fabric formed elements (West [17], West [18], West and Araya [19]).

In addition to the great possibilities of designing fascinating architectural shapes and optimized structures, there is also a technological advantage that should be considered. By casting concrete into a permeable membrane, excess pore water is allowed to bleed from the concrete during curing. The resulting reductions of water/cement ratio in the surface zone of concrete elements bring improvements in durability (Price [19]).

2.3 Shear Behaviour of tapered RC beams and FRC RC beams

Limited research focusing the structural behaviour of fabric formed steel reinforced concrete beams has been undertaken. Although some of the available test data suggest a propensity for variable cross sections to fail in shear, it was recently demonstrated that the EN 1992-1-1 [21] variable truss model might not be appropriate for the design of such structures (Orr et al. [22]). Similarly, shear behaviour of FRP reinforced concrete members is a very delicate issue that has been recently analysed in detail (Razaqpur and Isgor [23], Razaqpur and Spadea [24]).

Therefore, the numerical and experimental research to be undertaken by the authors will focus on the understating of shear behaviour of novel FRP RC optimized beams. In particular, the search for the optimal geometry of the FRP spirals will be driven by the distribution of principal tensile stresses.

3. Future Work

The use of filament wound carbon fibre has potential to greatly simplify the design and construction of optimised, flexibly formed concrete structures. For example, the complex optimised geometry of the slab and column system shown in Figure 3 would be difficult to reinforce with conventional steel bars; a knitted CFRP reinforcement system would provide a lightweight, easily manufactured, alternative.

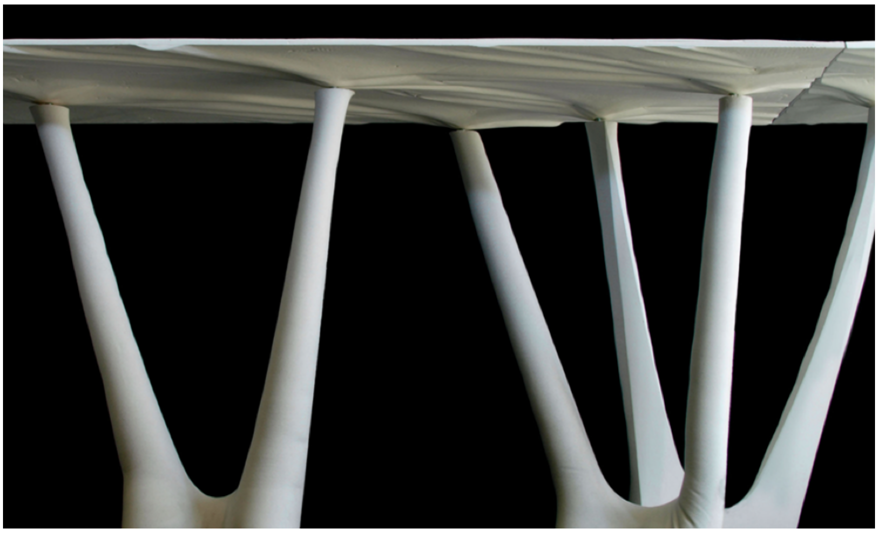

Figure 3: Image of a complex geometry fabric formed structure for which a novel reinforcement system may be appropriate - Image courtesy of West and Araya [19].

This research is currently in its early stages, and to ensure the full project goals are achieved future activities will include both theoretical investigations and laboratory tests. The experimental program will include two different stages: in the first phase, small-scale tests will be performed with the aim of exploring the effectiveness of the innovative web reinforcing systems. In the second phase full scale flexural tests will be conducted on optimized 4m span FRP RC T-beams in which knitted FRP spirals will be incorporated.

3.1 Preliminary Study

A preliminary study will be devoted to the assessment of current design methods with regard to key performance that are required for FRP reinforced concrete members. To ensure the reliability of these methods, detailed statistical analyses of their accuracy will be performed using experimental data available in the literature.

At the end of this phase, a clear picture of the reliability of predictive formulae proposed to date to evaluate the behaviour of FRP reinforced structural elements will be made available. This will give the opportunity to implement them in a code, so as to perform a section-by-section strength analysis of simply supported beams with variable cross section. The procedure will include an optimization process capable of determining the exact geometry of concrete beams and reinforcing cages depending on the loading scheme applied.

3.2 Characterisation Tests

Standard tests will be conducted on different kind of prototypes, with aim of setting up the manufacturing technology of the novel reinforcement.

- Tensile tests on straight FRP rebars (ACI 440 [25]);
- Tensile tests on FRP bent rebars embedded in concrete (ACI 440 [25]);
- Z-type push-off tests on FRP RC specimen (Hoffbeck *et al.* [27]);
- Three point bending tests on FRP RC prismatic specimens (BS EN 12390-5:2000 [26]);
- Pull out tests on FRP RC beam-end specimens (ACI 440 [25]).

At the end of this experimental phase, the mechanical properties of the FRP material produced by means of the filament winding will be determined. Furthermore, the best geometry and technology to produce such materials with the aim of being effective as concrete reinforcement will have been established.

3.3 Full Scale Tests

During the second phase of the research, the process of optimization of FRP RC beams will be refined in view of the experimental findings. The data obtained by testing the FRP reinforcement produced by filament winding, such as its actual tensile properties, FRP-to-concrete bonding law, strength on bent corners, shear resistance of an FRP RC section, will be instrumental in improving the mechanical model of FRP RC beams.

Some criteria of minimization of the volume of concrete and reinforcement will also be introduced into the optimization process, so as to obtain structural elements with minimal mass and minimal embedded energy. Finally, a number of full scale optimized FRP RC beams, with clear span equal to 4 m, will be designed and tested under three-point-bending.

The different prototypes will have different characteristics in terms of shear span, web reinforcement, longitudinal reinforcement and concrete strength.

The test results on scale prototypes will give the opportunity to draw conclusions sufficiently general to evaluate the effectiveness and usability of the new construction method proposed.

4. Significance and Expected Results

The long term goals of the research in progress at the University of Bath are several: from the impact of the outcomes on the construction field, to the relevance of these endpoints for the preservation of the built environment.

- Solving the issue of producing complex geometry, lightweight, ready to use, FRP reinforcement cages for both precast and in-situ construction;

- Positive economic impacts associated with the reduction of the quantity of concrete and FRP reinforcement to be used in FRP RC structures;
- Minimizing the environmental impact of constructions by revolutionising the way the concrete and reinforcement is used in structures and achieving the goal of low carbon design.

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Data Access Statement

All data created during this research are openly available from the University of Bath data archive at http://dx.doi.org/10.15125/BATH-00085.

References

[1] Veenendaal D., West M., Block P. History and overview of fabric formwork: using fabrics for concrete casting. *Structural Concrete*, 2011; **12**: 164-77.

[2] Orr J.J., Evernden M., Darby A.P., Ibell T.J. Proceedings of the Second International Conference on Flexible Formwork. *The Second International Conference on Flexible Formwork*. UK: University of Bath, 2012.

[3] Ahmad S.H. Reinforcement corrosion in concrete structures, its monitoring and service life prediction - A review. *Cement and Concrete Composites*, 2003: **25**:459–471.

[4] Plecnik J. and Ahmad S.H. *Transfer of composite technology to design and construction of bridges*. Final report to US DOT, contract no. DTRS 5683-C000043 (1988).

[5] Kaw A.K. *Mechanics of composite materials*, 2nd ed. Boca Raton, FL: Taylor and Francis (2005).

[6] Nanni A. *Fiber-reinforced-plastic for concrete structures: Properties and applications*. Amsterdam: Elsevier Science, 1993.

[7] ACI Committee 440. *Report on fiber-reinforced polymer (FRP) reinforcement for concrete structures*. ACI 440R -07, American Concrete Institute, Farmington Hills, MI (2007).

[8] Japan Society of Civil Engineering (JSCE). *Design guidelines of FRP reinforced concrete building structures*. Concrete engineering series no. 23, Tokyo, Japan (1997).

[9] ACI Committee 440. *Guide for the design and construction of structural concrete reinforced with FRP bars*. ACI 440.1R-06. American Concrete Institute, Farmington Hills, MI (2006).

[10] AASHTO LRFD. *Bridge design guide specifications for GFRP-reinforced concrete bridge decks and traffic railings*. Washington, DC: American Association of State Highway and Transportation Officials (2009).

[11] CNR Advisory Committee on Technical Recommendations for Construction. *Guide for the design and construction of concrete structures with fiber-reinforced polymer bars*, CNR-DT 203/2006. National Research Council, Rome, Italy (2006).

[12] fib. Bulletin 40, *FRP reinforcement in RC structures*. International Federation for Structural Concrete (FIB—Fédération Internationale du Béton), Lausanne, Switzerland (2007).

[13] CSA S6-06. *Canadian Highway Bridge Design Code*. Canadian Standard Association, Toronto, Ontario, Canada (2006).

[14] CSA S806-12. *Design and Construction of Buildings Components with Fiber-Reinforced Polymers*. Canadian Standards Association, Toronto, Ontario, Canada (2012).

[15] Nanni A., De Luca A., Jawaheri Zadeh H., *FRP Reinforced Concrete Structures – Theory, Design and Practice*, CRC Press, April 3, 2014, 400 pp. 978-0-415-77882-4.

[16] Heath A, Paine K., Reducing CO_2: Optimum blend of binders in the UK, In *34th Annual Conference on Cement and Concrete Science*, Sheffield, UK: University of Sheffield, 2014.

[17] West M. Fabric Formed Concrete Members*, Concrete International* 2003*,* **25**(10), 55-60.

[18] West M., Abdelgader H.S., Gorski, J. State-of-the-Art Report on Fabric Formwrk, *Concrete: Construction's Sustainable Option*, Dundee, UK, 4-6 September 2007.

[19] West M, Araya R. Recent fabric formwork construction projects. In: Orr JJ, Evernden M, Darby AP, Ibell PT, editors. Second International Conference on Flexible Formwork. University of Bath: Bath; 2012.

[20] Price, W.F., *Controlled permeability formwork*, Construction Industry Research and Inforation Association, London, 2000.

[21] EN 1992-1-1, *Eurocode 2: Design of Concrete structures – Part 1-1: General rules and rules for buildings*, 2004.

[22] Orr J.J., Darby A.P., Ibell T.J., Lava P., Debruyne D. The shear behaviour of non-prismatic concrete beams determined using digital image correlation. In: Dirckx J, editor. 5th International Conference on Optical Measurement Techniques for Structures and Systems 2012. Antwerp, Belgium2012.

[23] Razaqpur A.G. and Isgor O.B.. Proposed shear design method for FRP-reinforced concrete members without stirrups. *ACI Structural Journal* 2006, **103**(6), 908.

[24] Razaqpur A.G., Spadea S. Shear strength of FRP reinforced concrete members with stirrups, *Journal of Composites for Construction* 2014, **19** (1), art. no. 04014025.

[25] ACI Committee 440, *Guide test methods for fiber-reinforced polymers (FRPs) for reinforcing or strengthening concrete structures*. ACI 440.3R-12. American Concrete Institute, Farmington Hills, MI (2012).

[26] EN 12390-5, *Testing hardened concrete. Flexural strength of test specimen*, 2009.

[27] Hoffbeck J.A., Ibrahim I.O. & Mattock A.H. Shear transfer in reinforced concrete. *Journal of the American Concrete Institute* 1969 **66** (2) 119-128.